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An Experimental Investigation into the Feasibility of a Thermoelectric Heat Flux Gage

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SUMMARY

An experiment was conducted to determine the feasibility of using a commercially available thermoelectric device as a heat flux gage. In certain research applications, the thermoelectric heat flux gage can provide a relatively simple means to model a warm fluid--cold wall. The experiment showed that heat flux through the gage could be correlated within two percent to the applied thermoelectric current through the device and the hot and cold side temperatures with a simple algebraic equation.

NOMENCLATURE

α	Seebeck parameter, volt/K
I_{TED}	TED current, ampere
k	Heat conduction parameter, watt/K
q_c	Heat flux at cold plate, watts
q_k	Heat conducted, watts
q_l	Heat loss, watts
q_{lc}	Heat gain at cold plate, watts
q_p	Peltier heat, watts
q_R	Resistence heat, watts
R	Resistence parameter, ohms
T_{amb}	Ambient temperature, K
T_c	Cold plate temperature, K
T_g	Guard plate temperature, K
T_H	Hot plate temperature, K
ΔT_w	Water temperature rise, K

INTRODUCTION

A common method of making heat transfer measurements and determining heat transfer coefficients between a surface and a flowing gas is to use an electric heater attached to the surface in conjunction with surface and gas temperature measurements. A properly guarded heater can supply a simply measured amount of heat. The heat transfer coefficient can be found by dividing the measured heat flux by the differences in these temperatures. Using this method a temperature gradient is set up with the wall warmer than the flow. This has been done at various laboratories to measure the heat flux distribution around a simulated turbine blade; see for example references 1 and 2. A recent workshop at Lewis on heat transfer research in gas turbine engines questioned the confidence researchers have in this method of obtaining heat transfer data, when in the actual turbine the direction of heat flux is from gas to blade (reference 3).

The reason for such concern is that a heated laminar boundary layer will transition to turbulent flow at a lower Reynolds number than an unheated boundary layer. This has been shown experimentally by Linke and analytically by Tollmien (reference 4). For research applications where the heat flux is into the wall and where the condition of the boundary layer is important (as in turbine blade heat transfer) the electric heater heat flux gage may not be the appropriate instrument. A gage which removes a measurable amount of heat from the surface in a controllable manner would prove useful.

A method of measuring the heat flux which involved removing heat from the fluid was used in reference 5. In this method a cold fluid was circulated in passages beneath the surface while a heated gas flowed over the surface. Gardon type gages then measured the local surface heat flux. This method is cumbersome involving pumps for liquid flow, heating of the gas, and a large amount of sensitive instrumentation producing microvolt signals.

Thermoelectric devices, which are small commercially available solid state heat pumps, can provide a means of cooling a surface. The thermoelectric device (TED) is simply an array of paired semiconductor junctions which, when energized, moves heat from one junction to the other. Because the rate of heat pumping is proportional to the current used, it was thought these devices could be used as a heat flux gage in low temperature research applications where the heat flux direction must be toward the surface.

A limited amount of work has been published concerning thermoelectric devices. Manufacturers product catalogs and application notes give general information on the use of their products (references 6, 7, and 8). References 9, 10, and 11 provide theoretical background for thermoelectric materials and processes. A survey of the literature shows only a few papers in this area. Most of these sources, however, are concerned with TED use in refrigeration applications where the amount of heat to be pumped is approximately constant; and so, only of concern during initial design of the appliance. These data are of marginal use in predicting the characteristics of a thermoelectric heat flux gage. The heat flux gage will operate at varying temperatures and power levels. To make this device useful as a heat flux gage, a simple way to correlate heat flux to the TED operating parameters is needed.

The objective for this preliminary study was to determine if a thermoelectric device could be used practically as a heat flux gage. A prototype thermoelectric heat flux gage has been built. The gage consists of a readily available TED sandwiched between two copper plates one of which has provisions for water cooling. For this experiment an electric heater was used as a source of heat to be removed by this gage. Data, when reduced, provided the rate of heat pumping as a function of the TED operating parameters. These data were also used to check the validity of an equation relating TED parameters and heat pumped through the device.

GENERAL THERMOELECTRIC THEORY

The thermoelectric device (TED) is a solid state heat pump. It is an array of paired N and P semiconductor junctions. Figure 1 shows a single semiconductor pair. If a temperature difference is held across the two junctions an electrical potential appears at the terminals of the device. This is the Seebeck effect (simple thermocouple effect). As shown in Figure 1, however, when a source of current is applied across the TED one junction becomes cold, the other hot. This is the Peltier effect.

For use as a heat flux gage it is necessary to be able to determine the amount of heat being removed from the cold side of the device. There are three basic modes of heat transfer in a TED:

Peltier Effect--The Peltier effect is the heat pumping process when the device is energized. It includes only the heat that would not otherwise be moved from the cold to hot side

$$q_p = \alpha I_{TED} T_c \tag{1}$$

(q is designated as positive when it flows from cold to hot side)

Heat Conduction--Because the unit produces a temperature gradient there will be heat conducted through the device. It is important to note that this heat travels from hot to cold side and so is taken as negative.

$$q_k = -k(T_H - T_c) \tag{2}$$

Resistance Heating--Electric power input to the device creates heat which is assumed dissipated equally on both the hot and cold side. In considering TED's use as a heat flux gage we only need to consider heat dissipated at the cold side. Thus,

$$q_R = \frac{-I^2_{TED} R}{2} \tag{3}$$

Combining these terms yields an expression for the heat removed from the cold side

$$q_c = \alpha I_{TED} T_c - k(T_H - T_c) - \frac{I^2_{TED} R}{2} . \tag{4}$$

The purpose of this study was to determine if equation 4 could be used to calibrate a TED for use as a heat flux gage. If the parameters α, R, and k are constant over a useful range of temperatures then the TED should prove a practical research tool.

APPARATUS

Thermoelectric devices are commercially available in a wide range of sizes and capacities. Sizes are available from just a few square millimeters to several square centimeters. Thickness of these devices is usually from .4 to .5 centimeter. The maximum rate of heat pumping is from about one quarter watt to more than 35 watts. Temperature limits, which are due to the semiconductor material properties, are normally 373 to 423 K.

One of the many TEDs available on the market was chosen as representative for this preliminary investigation. This device was 3.96 cm (1.56 inches) square and 0.381 cm (0.15 inches) thick. There were 127 semiconductor pairs. The semiconductor was a quarternary alloy of bismuth, tellurium, selenium, and antimony.

For use as a heat flux gage, in this experiment two 0.635 cm (1/4 inch) thick copper plates were attached to each side of the TED. Both plates were fitted with four chromel-alumel thermocouples soft soldered in grooves on the face that adjoins the TED. The thermocouples were fabricated following the recommendations in reference 12. Figure 2 is a sketch of the test apparatus. Since heat flow was from the cold side to the hot side a .476 cm (3/16 inch) O.D. copper tube was soldered to the hot side plate to remove heat. Two Cr-Al thermocouples recorded inlet and exit water temperature difference. Cr-Al thermocouples also measured ambient temperature on the outside of the insulation surrounding the test TED gage. The copper plates were attached to the TED using the manufacturer's recommendations. The hot side of the TED was soldered to the copper plate using a low temperature indium-tin solder. The cold side was in mechanical contact with the copper plate and a thin layer of silicon heat sink compound was used to insure low thermal contact resistence.

The calibration procedure required that an easily measured amount of heat be supplied to the cold plate of the gage. This was accomplished with a self-adhesive metal foil electric heater. This heater was attached directly to the exposed surface of the cold side copper plate. Finally, another copper plate and electric heater were used as a guard to eliminate heat losses from the cold side plate during the heat loss calibration. The whole assembly was surrounded with insulation to minimize heat loss to the surroundings.

PROCEDURE AND DATA REDUCTION

Heat Loss Calibration--During the actual running of the gage it will be necessary to know the amount of heat moving through the cold plate. In this experiment, this was done by knowing the amount of heat supplied by the electric heater. However, because the TED keeps the temperature of the cold plate, T_c, less than ambient temperature, T_{amb}, additional heat, designated q_{lc}, will "leak" into the cold plate. The purpose of the heat loss calibration was to find this heat gain as a function of the temperature difference, $T_{amb} - T_c$.

The heat loss calibrations were actually conducted in reverse; during calibration tests heat was lost from the device while during actual running as a gage heat was gained by the TED. The heat loss calibration was performed with the TED unenergized. The water flow was set to an arbitrary rate. The electric heater was adjusted to the approximate $T_{amb} - T_c$ desired. The guard heater, which was used only during heat loss calibration, was adjusted so T_g equaled T_c; this ensures all the heat supplied by the heater flows into the cold plate. When equilibrium was reached (normally several hours) the inlet and exit water temperature, flow rate, power input to the electric heater, and all temperatures were recorded.

At equilibrium the difference between heat input and heat carried away by the flowing water is the heat loss at a specific $T_{amb} - T_c$. This heat, q_l, is lost from both the hot and cold plates. When the gage operates, however, we are concerned only with the heat gained by the cold plate, q_{lc}. Therefore, the heat gain was taken as one-half the heat loss at similar $T_{amb} - T_c$.

Figure 3 shows the experimental heat loss data and the line of best fit. A linear regression analysis of this data yields:

$$2q_{lc} = q_l = 0.0003\ (T_{amb} - T_c) + 0.261 \qquad (5)$$

Because the slope is very small and the temperature difference is generally small, heat loss was taken as constant (.261 watts) over this temperature difference range.

Thermoelectric Heat Flux Gage Calibration--Because of a limited ability to control hot plate temperature it was decided to run all calibrations at T_H = 303 K. The guard heater was not used because cold plate temperatures lower than ambient were obtained. The cold plate heater was arbitrarily set while I_{TED} and water flow rate were adjusted to maintain T_H = 303 K and the desired cold plate temperature, T_c. At equilibrium all data were recorded and a new point was set by changing the heater power and readjusting I_{TED} and the water flow rate to maintain T_H and T_c. The heat pumped by the device was assumed equal to the electric heater input plus the heat gain, q_{lc}, (Equation 5).

RESULTS

The data gathered during the experiment were fit to equation (4) by the method of least squares. It was expected that for the range of temperatures and heat flows used the parameters α, R, and k would be constant. Good correlation of the data and the least squares curve fit supports this expectation. Values found were:

$$\alpha = 0.048 \text{ volts/K}$$
$$R = 2.30 \text{ ohms}$$
$$k = 0.539 \text{ watts/K}$$

Using these constants in equation (4) (with T_H = 303 K) the heat removed from the cold plate can quickly be found by measuring T_c and I_{TED}. The reader is cautioned that the constants determined herein may not be generally applicable. The device should be calibrated for each particular research application.

The experimental data and equation (4) are plotted together in figure 4. Several data points were repeated and show excellent agreement. Average error between data and calculation using the above constants is slightly less than two percent.

During the tests the operating parameters of the TED were found to be stable as long as water temperature, flow rate, and current were kept constant for periods of several hours. There is no reason to suspect the device will not be stable indefinitely. From figures 3 and 4 it can be seen that the heat gain, q_{lc}, is a small fraction of the heat pumped by the device.

SUMMARY OF RESULTS

A prototype thermoelectric heat flux gage has been built and calibrated for a limited temperature range. This device uses an inexpensive, off-the-shelf, thermoelectric device which requires little modification. In heat transfer research applications where it is important to model a warm fluid--cold wall the thermoelectric heat flux gage could be a useful instrument.

Results of the investigation can be summarized as follows:

1. Correlation of the data and the least squares curve fit to within two percent shows the form of the general equation (equation (4)) is correct for this application. One set of constants covers a fairly wide range of cold plate temperatures and heat flows.

2. Data taken shows good repeatability.

3. The operating parameters of the thermoelectric heat flux gage were found to be stable.

CONCLUSIONS AND RECOMMENDATIONS

The success of this preliminary study shows a thermoelectric heat flux gage is feasible.

Manufacturer's literature notes that the rate of heat pumping is dependent on the hot side temperature (T_H). Experiments are needed to determine if equation (4) can be used for arbitrary values of T_H and whether the parameters α, R, and k are true constants or functions of T_H.

Another point to consider is the effect of average temperature of the gage on the parameters α, R, and k. Since the temperature limitations of the device (due to semiconductor properties) cover a fairly wide range, the device could be used at nominal temperatures very much higher or lower than the temperatures used in this experiment.

A final point which was not addressed in this study is the effect of TED size on its use as a heat flux gage. For ease of handling and instrumentation a rather large TED was used for these experiments. It is probable that in some experiments a smaller heat flux gage will be needed. An investigation of the effect of size on thermoelectric heat flux gages should also be done.

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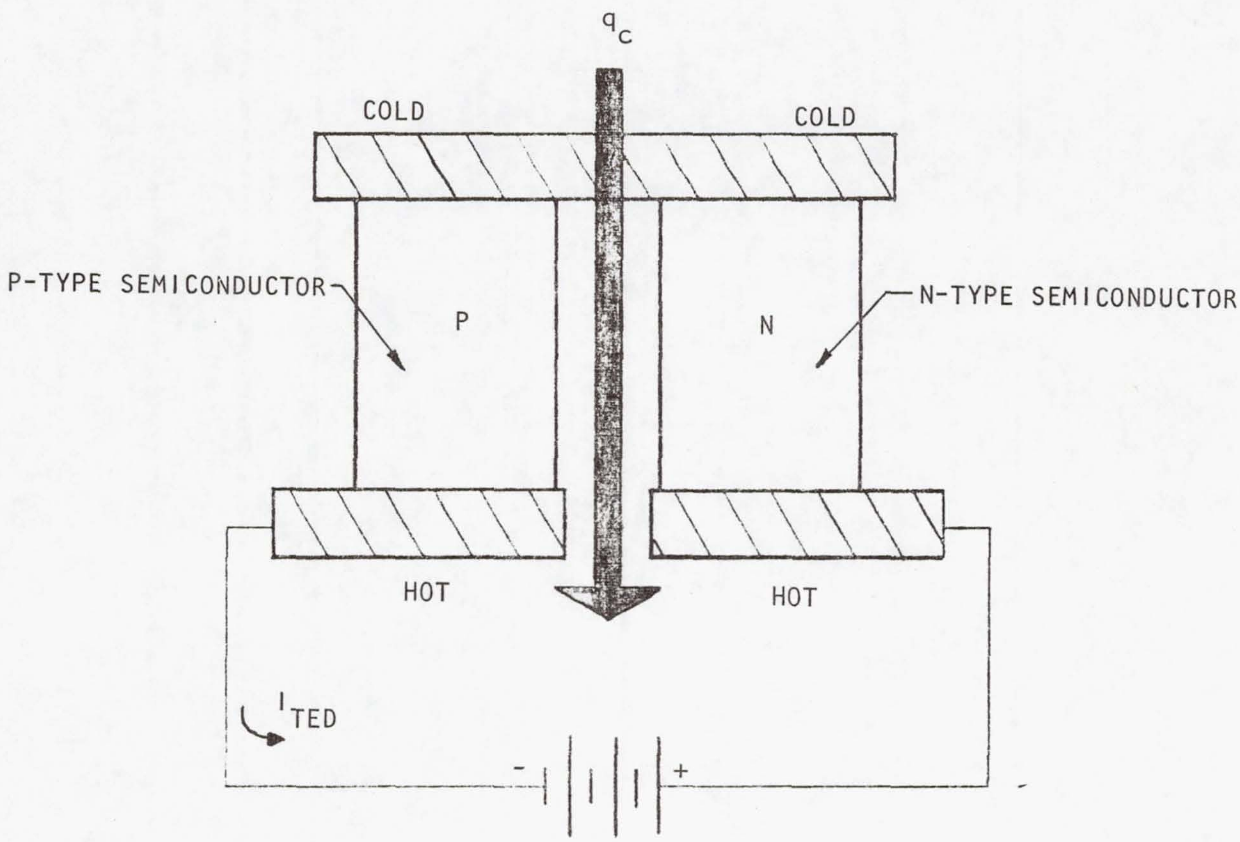

Figure 1. Typical thermoelectric couple.

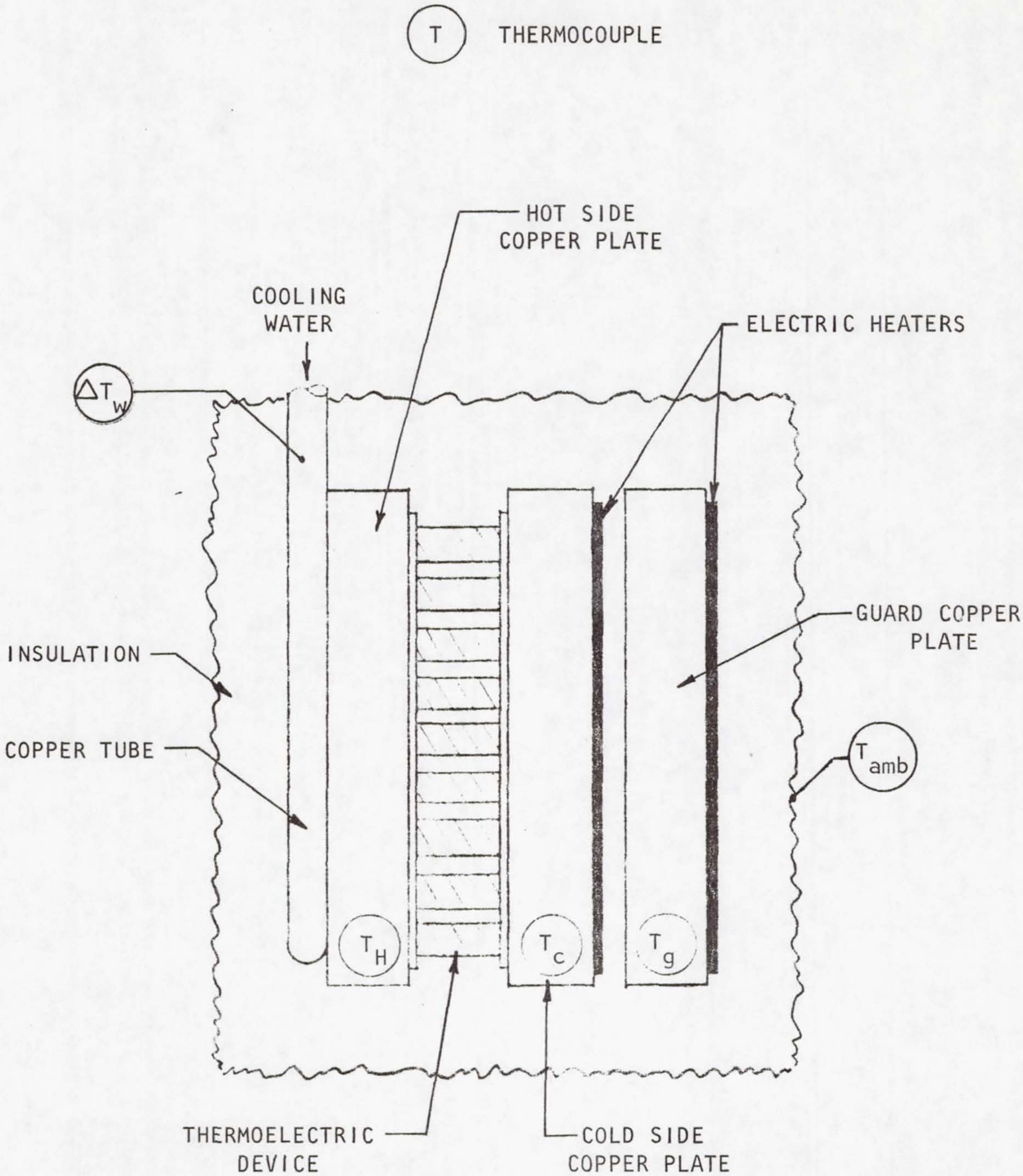

Figure 2. Thermoelectric heat flux gage calibration rig.

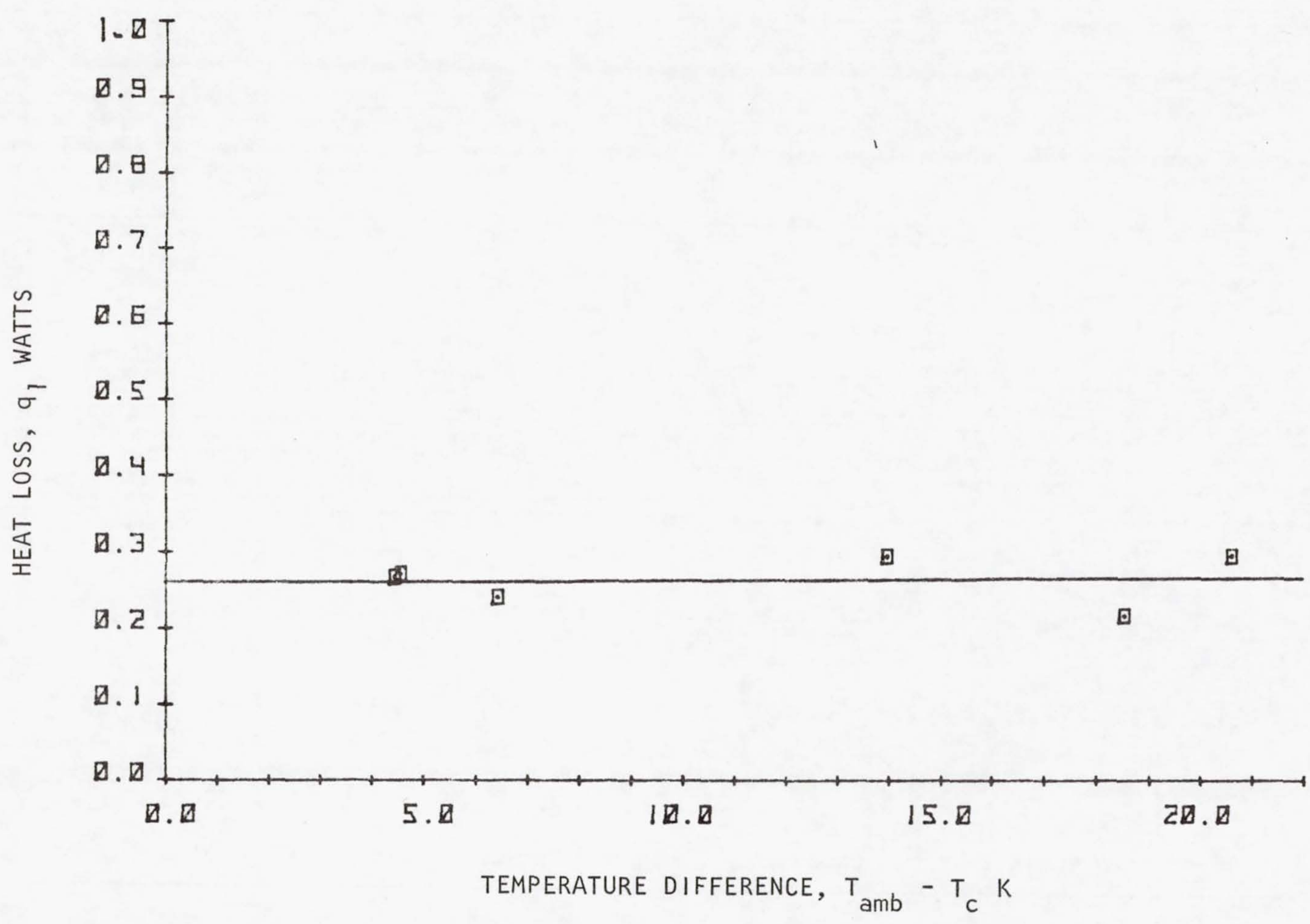

Figure 3. Heat loss calibration curve.

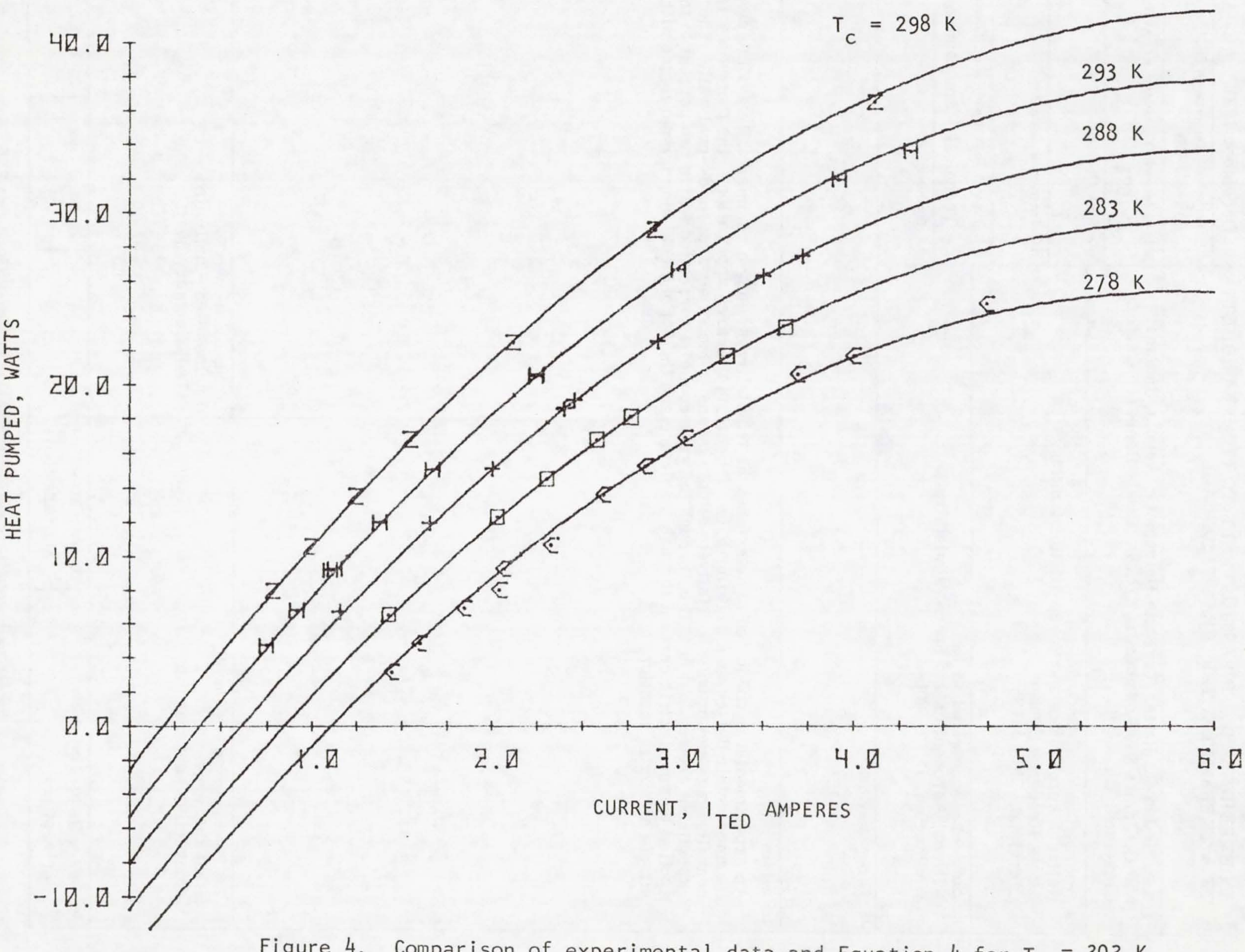

Figure 4. Comparison of experimental data and Equation 4 for T_H = 303 K

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15. Supplementary Notes

16. Abstract

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